Microelectronics Journal 39 (2008) 1083–1092

Microelectronics Journal

www.elsevier.com/locate/mejo

Compound noise separation in digital circuits using blind source separation

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Received 26 October 2007; received in revised form 15 January 2008; accepted 21 January 2008
Available online 18 April 2008

Abstract

Analysis of individual noise sources in pre-nanometer circuits cannot take into account the evolving reality of multiple noise sources interacting with each other. Noise measurement made at an evaluation node will reflect the cumulative effect of all the active noise sources, while individual and relative severity of various noise sources will determine what types of remedial steps can be taken, pressing the need for development of algorithms that can analyze the contributions of different noise sources when a noise measurement is available. This paper addresses the *cocktail-party problem inside integrated circuits* with multiple noise sources. It presents a method to extract the time characteristics of individual noise source from the measured compound voltage in order to study the contribution and properties of each source. This extraction is facilitated by application of blind source separation technique, which is based on the assumption of statistical independence of various noise sources over time. The estimated noise sources can aid in performing timing and spectral analysis, and yield better circuit design techniques.

Keywords: Adaptive signal processing; Blind source separation; Compound noise separation; Integrated circuit noise; Independent component analysis

1. Introduction

With rapid scaling of VLSI technology into nanometer scale, digital integrated circuits have been affected by similar noise problems as analog integrated circuits have been since their inception [1]. As the noise margins are decreasing, circuits are becoming increasingly vulnerable to different types of noise, such as, capacitive and inductive crosstalk, charge sharing, leakage, IR drop, Ldi/dt noise, substrate coupling, power supply noise, ground bounce and alpha particle radiation-induced soft-errors [1]. Traditionally, noise analysis characterizes individual noise sources separately, and assigns maximum individual budget to each of them [2]. However, this approach is sometime conservative, since not all simultaneously active noise sources impose worst-case affects on a particular evaluation node at a particular instant of time; while some approaches ignore the fact that multiple noise sources can combine to magnify each other, greatly increasing the possibility of errors [2]. In nanometer scale circuits, where the margins of tolerance are very stringent, a rather desirable approach is to adopt a three-step technique for noise analysis:

- Identify nodes that are sensitive to noise
- Evaluate the compound noise effects on those nodes
- Identify contributing noise sources when a noise measurement is available

To identify the spots or nodes in the circuits, which are most susceptible to noise sources, we can use existing algorithms like Automatic Soft Spot Analyzer (ASSA) [3]. However, it is more important to detect various noise sources, which affect these soft spots to cause an error, since noise measurements made at any evaluation node will reflect the cumulative affect of all the noise sources.

Sometimes one noise source may combine with other noise sources, and make the evaluation node more vulnerable to signal integrity problems. The simplest way

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0026-2692/$ - see front matter
doi:10.1016/j.mejo.2008.01.070

to model compound noise effect at a particular circuit node is through linear superposition of different noise sources [2]. Due to the non-linear behavior of gates through which noise propagates in the circuit, the linear combination of noises might seem fallible. However, for small signals, drivers and the gates in the circuits can be replaced by linear models [4], which accurately combine propagated and injected noise on a net, while maintaining the efficiency of linear simulation. However, in order to better estimate the compound effect, it is necessary to determine whether a linear superposition of concurrent noise sources is sufficient or the noise sources are going to mix in a non-linear manner. Since there is no work addressing this issue, we assume in this paper, for simplicity, linear superposition of noise sources.

Although studying the cumulative effect of all noise sources is important, it is imperative to identify the contributing noise sources when combined noise measurement at a particular evaluation node is available. Therefore, a technique to separate individual noise voltages from the combined measured noise voltage will be an efficient tool to avoid over or under design from noise tolerance point of view. The purpose is to estimate the time profile of each contaminating noise because it:

- Allows estimating the contributions from different noise sources.
- Helps us to study the time variation or spectral properties of each noise source.
- Leads to the development of techniques to tackle each noise source independent of other sources.

This paper presents an algorithm to separate noise sources affecting an evaluation node by utilizing information about either the current or voltage waveforms of compound noise at the nodes. In order to develop such an algorithm, we use *blind source separation* (BSS) [5–8] based technique, which is a well known digital signal processing algorithm used to extract statistically independent sources from their observed linear mixtures. BSS algorithms make no prior assumption about the characteristics of the unknown mixing sources except about their mutual independence. The rest of the paper is organized as follows. Section 2 proposes the concept of cocktail-party problem in a circuit network, and describes how linear superposition principle can be used to study the effects of various noise sources on an evaluation node. Section 3 introduces the basics of BSS while Section 4 presents its algorithmic implementation. Section 5 presents experimental results and discussions. Finally, Section 6 concludes the paper with some insight into our ongoing research.

2. Linear superposition of noise sources

A classical example of BSS is the cocktail-party problem. Assume that several people are speaking simultaneously in the same room, as in a cocktail party. In this situation, the problem is to separate the voices of the different speakers, using recordings of several microphones in the room [9]. Let x denote an m-dimensional random variable, which represents the recorded speech signals; the problem is then to find a function f so that the n-dimensional transform $\mathbf{s} = (s_1, s_2, \ldots, s_n)^{\mathrm{T}}$ defined by Eq. (1)

$$\mathbf{s} = f(\mathbf{x}), \tag{1}$$

has some desirable properties. In most cases, the representation is sought as a linear transform of the observed variables, i.e.,

$$\mathbf{s} = \mathbf{W}\mathbf{x}, \tag{2}$$

where $\mathbf{W}$ is a matrix to be determined. Using linear transformations makes the problem computationally and conceptually simpler, and facilitates the interpretation of the results.

The above case is similar to what happens in a circuit network with several noise sources injected at different circuit nodes. For example, in the circuit shown in Fig. 1, there are three noise sources v_1, v_2 and v_3 and we measure the noise signals at three different nodes A, B and C. If all the components in the circuit are assumed to be linear, the measured signals V_{A}, V_{B} and V_{C} will be the linear combination of the three noise sources. If we want to separate these signal sources from their measured combinations, this problem is just another version of the *cocktail-party in a circuit network*.

As an example of a real digital circuit consider the three-input NAND gate shown in Fig. 2. Denote by $V_{\mathrm{a}}(t)$, $V_{\mathrm{b}}(t)$ and $V_{\mathrm{c}}(t)$ the voltages at nodes A, B and C, respectively. Let us denote the various noise sources by: $V_{\mathrm{cc}}(t)$ = cross-coupling noise, $V_{\mathrm{ls}}(\mathrm{t})$ = leakage or substrate noise and $V_{\mathrm{ps}}(t)$ = power supply noise.

The total voltage at ith arbitrary node, assuming it to be at the logic level '0', can be written as in Eq. (3), where ms are the various unknown contributing factor of different noise sources:

$$V_i(t) = m_{1\mathrm{i}} V_{\mathrm{cc}}(t) + m_{2i} V_{\mathrm{ls}}(t) + m_{3i} V_{\mathrm{cs}}(t), \tag{3}$$

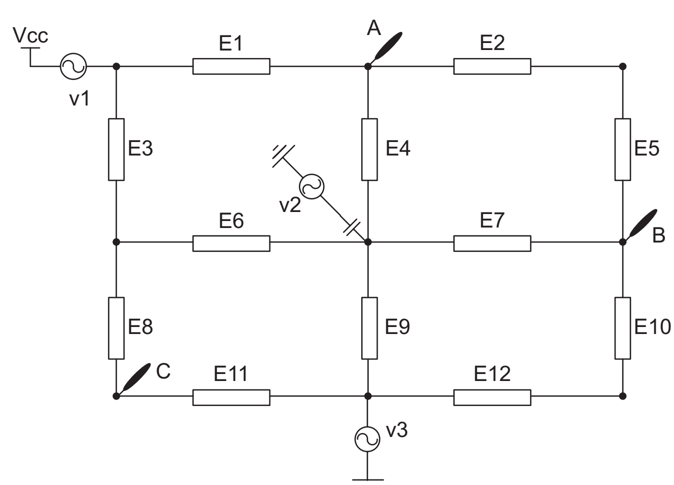

Fig. 1. Cocktail-party problem in a circuit network.